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DEVELOPMENT PHASE COST DRIVERS FOR PRODUCTION COSTS: THE CASE OF TRACKED VEHICLES

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Development Phase Cost Drivers for Production Costs: The Case of Tracked Vehicles

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ABSTRACT

There are two different approaches, the disjoint and sequential models, which attempt to account for differences between development unit cost and production unit cost. The disjoint model uses a production cost improvement curve that is physically separate from the development cost improvement curve. For the sequential model, however, the first unit cost of production units directly follows the last development unit due to a carryover of the cost improvement process. This paper, using a sample of seven tactical armored tracked vehicles, first obtains the theoretical first unit production costs for the vehicles under both sequential and disjoint models. Then, using various measures of activities in the development phase, CERs are obtained for both models which relate activities in the development phase to theoretical first unit production cost. The results indicate that, for the disjoint model, first unit production costs depend on development first unit costs. For the sequential model, first unit production costs depend on the average development cost as well as the time span between the end of development and the beginning of production.

INTRODUCTION

A number of different methods are currently used to estimate first unit production cost for a new weapon system. Most of these methods rely upon empirically-derived cost improvement, or learning, curves for the production phase of the weapon system. The difficulty with these current methods is that they require some knowledge of the production phase of the system's life cycle. Since estimates of production costs are normally required well before the system enters its production phase, "knowledge" of production-phase characteristics for this new system is actually a set of assumptions. An alternative approach is to utilize information already available during the development phase to estimate first unit production costs. Such a technique could be based on established relationships between development phase variables and first unit production costs. This paper explores this development-to-production estimation technique using a sample of tracked vehicles.

When using this development-to-production technique, the nature of the transition between the two phases becomes important. There are two different theories, the disjoint and sequential models, which attempt to account for the relationships between development unit costs and production unit costs. The disjoint model uses a production cost improvement curve that is separate from the development cost improvement curve. In the case of the sequential model, however, the first unit cost of production units directly follows the last development unit due to a carryover of the cost improvement process.

This paper, using a sample of seven tactical armored tracked vehicles, first obtains the theoretical first unit production costs for the vehicles under both sequential and disjoint models. Then, using various measures of activities in the development phase, cost estimating relationships (CERs) are obtained for both models which relate activities in the development

phase to theoretical first unit production cost. The results indicate that, for the disjoint model, first unit production costs depend on development first unit costs. For the sequential model, first unit production costs depend on both average development costs and the time span between end of development and beginning of production.

DEVELOPMENT-TO-PRODUCTION THEORIES: DISJOINT VERSUS SEQUENTIAL

The two development-to-production theories imply different characteristics of the transition from the development phase to the production phase of a new system. The disjoint model assumes that the production cost improvement curve is physically separate from the development cost improvement curve. This model implies that any "learning" (or, more precisely, cost improvement) that occurs during the fabrication of development units is not transferable to production units, and therefore, will not affect production costs.

The sequential model differs from the disjoint model in that the first unit cost of production units follows the last development unit. The sequential model states that "learning" gained in development is carried over to production. Sequential modeling typically allows discontinuities, such as a decrease in unit cost, in the cost improvement curve between the last development unit and the first production unit.

Both models allow the slopes of the development learning curve and the production learning curve to be different, but they do this in different ways (Gardner, et al., 1990). Differences between the two models and how their interpretations can affect unit cost can best be explained in terms of acquisition strategies.

The disjoint model suggests a program with discrete phases during development. Phases are introduced as part of acquisition strategy in order to provide periodic program

assessment and to assist in engineering project management. While the disjoint approach is suitable for ensuring that the projected system is operationally and fiscally sound, the effect of "learning" during development does not carry over to production. The goal during development under this strategy is information; therefore, only information relevant to the specific program goal is sought. (Perry, 1971)

The sequential model implies an ongoing assessment, redefinition and readjustment of a program. By doing this, program cost, performance objectives, and schedule changes, among other variables, are evaluated as part of an ongoing effort. As a result of this approach, "learning" during the development phase is transferred to the production phase. (Perry, 1971)

Figure 1 is a graphic representation of the disjoint model. The first production unit is defined as unit one on the production learning curve, T_{1P}. The development learning curve is drawn as flat, or indicating a 100% learning rate. First unit development cost is shown at point T_{1D}. Development quantity, Q_D, is the number of development units. Figure 1 indicates one way in which there is no carryover of knowledge in producing development units to producing production units; the T_1's are essentially independent.

A graphical representation of the sequential model is shown in Figure 2. The first production unit, T_{1P}, is displaced from the y-axis by the number of development units, Q_{D+1}. The additional unit is added because the first production unit is actually the next unit after the last development unit. First unit development cost is shown at point T_{1D}.

As a practical matter, there are few examples of either pure sequential or pure disjoint transitions. Most programs demonstrate varying degrees of each. Prior studies have demonstrated no clear occurrence of one over the other (Allard, et al., 1990). In this analysis, development and production first unit costs will be calculated and CERs established

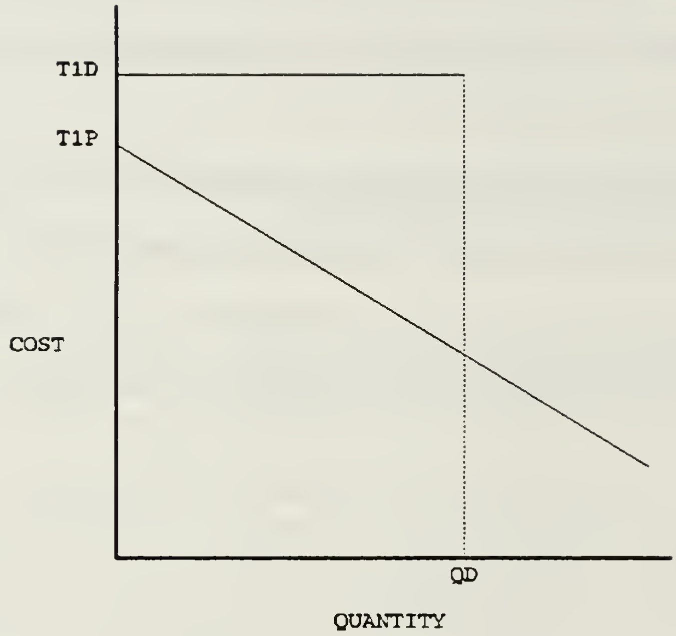

Figure 1: DISJOINT THEORY

using both methods for purposes of comparison and evaluation.

SAMPLE DATA DEVELOPMENT

The basic requirement for estimating costs by any means is a reliable data base. The quality of an estimate will be no better than the data it is based on. The data collected for this study is structured for use in developing relationships between the prototype manufacturing costs of development units and the recurring costs of production units for seven armored tracked vehicle programs.

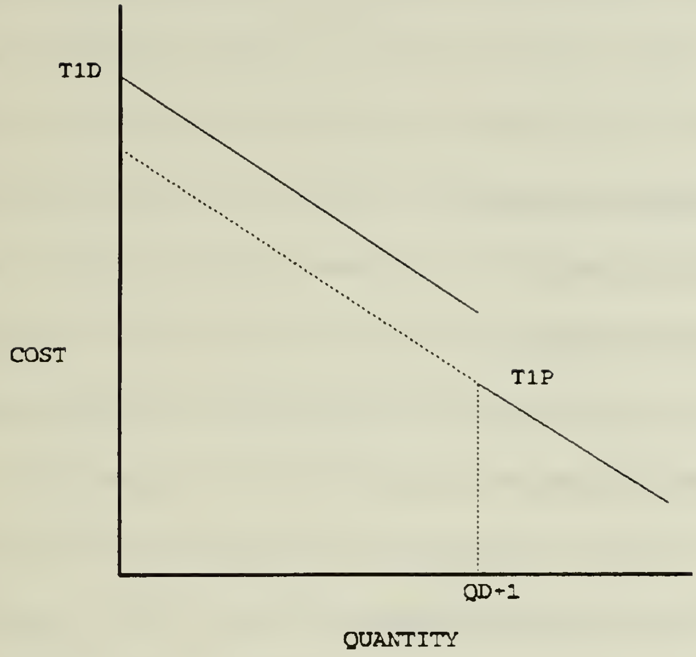

Figure 2: SEQUENTIAL THEORY

1. Program Candidate Selection

The data base consists of cost and quantity data for seven tracked vehicle systems. The size of the data base was determined by the number of systems for which data was available for both development costs and production costs.

Data points from seven armored tactical vehicle programs are used in examining the relationship between development cost and production cost. Many of the systems have been produced over several years, with upgrades and different variants of the basic vehicle. The upgrades and variants were considered to be modifications to existing systems, so they were not included. The reasoning is that development unit cost of a modified system would be unusually low relative to the other systems as a result of commonality with the original

vehicle. The data for the candidate systems is therefore limited to the original models and variants, even though in most cases the programs continued for many years. The seven systems are:

- M-1 ABRAMS TANK
- M-60 COMBAT TANK
- M-113 ARMORED PERSONNEL CARRIER
- M-2/3 BRADLEY FIGHTING VEHICLE
- M-109 SELF PROPELLED HOWITZER
- M-110 SELF PROPELLED HOWITZER
- LVTP-7 LANDING VEHICLE TRACKED

2. Cost Definitions

Development and production costs were collected for the candidate systems. In order to make all data points comparable, it is necessary to determine what part of development and production costs should be included. In the case of development costs, the prototype manufacturing cost is used. In the case of production costs, recurring production costs of the vehicle system are used.

Production costs include recurring and non-recurring costs. Recurring costs must be incurred each time a unit of equipment is produced. These costs include, for example, direct labor and direct materials. Non-recurring costs are expended at the beginning of a program to establish the specific capability to manufacture the weapon system. These costs are one-time expenditures and generally include such things as special tooling, special equipment, plant rearrangement, and the preparation of manufacturing instructions. (Acker, 1989)

These costs can be determined from available data sources, and most accurately

reflect the data points necessary to examine relationships between development and production costs. Recurring production costs are a function of the number of units produced; non-recurring costs are not. Non-recurring costs can include costs not associated with the actual production of the unit, as in the case where a contractor is allowed to fund development work on new projects by charging it off as an operating expense of a current project (Batchelder, et al., 1969). For this reason, recurring production cost was considered the best measure of specific hardware costs for each of the candidate systems. To provide consistency with production cost data, prototype manufacturing cost was chosen as the logical counterpart for development cost data.

The method of determining prototype manufacturing cost for each system was necessarily different for each of the programs because of the data available. Historical data on programs dating back to 1956 were not detailed enough to provide prototype manufacturing cost. Data on current programs, such as the M-1 and Bradley Fighting Vehicle, required analysis of Cost Performance Reports (CPRs) to determine prototype manufacturing cost. Specific details on how this was done are included with the vehicle descriptions.

3. Data Sources

Cost data were collected from several sources. Various editions of *Jane's Armour and Artillery* were used to narrow the population for this study. *Jane's* provided consistent information on program length, upgrades of the same system and general operating characteristics. This information also included the Research and Development (R&D) periods and the number of prototypes produced for some programs. The R&D periods and prototype quantities for older programs were necessary because contract data obtained for this study did not include this information. Data Source Associates publications provided missing data elements and served as a second source for some current programs (Nicholas).

Data for the M-1 was obtained from numerous sources. CPRs from FY80 to FY89 were used for the M-2/3. Contractor data was obtained for the M113, M109 and M110. This information contained complete histories of the vehicles from development through production. M-60 data was obtained from "An Evaluation of Competitive Procurement Methodologies Applicable to the Advanced Assault Amphibian Vehicle" (Corcoran, 1988). LVTP-7 data was obtained from "A Case Study of the LVTP-7 Amphibian Tractor Program" (Bahnmaier, 1974).

4. Data Normalization

To be useful for comparative analysis, cost data for the identified programs had to be normalized for consistency with respect to work breakdown structure, escalation indices, and expenditure profiles.

Work Breakdown Structure (WBS)

The WBS provides a segregation of recurring costs for development and production units. This segregation was used to reduce ambiguity concerning the content of recurring cost elements between systems in the data base. For development units, costs were identified as prototype manufacturing cost. Production unit costs were the recurring portion of the primary vehicle cost at Level 2 of the WBS.

Inflation Indices

Department of Defense approved indices for Army R&D and Army Surface Weapons and Vehicles were used to normalize data to millions of FY92 constant dollars. R&D deflators are applied to development units and Surface Weapons and Vehicle deflators are applied to production units.

Expenditure Profiles

When actual expenditures were known by year over an R&D phase or

production lot, they were used directly. Each year's expenditures were divided by the appropriate year index to obtain FY92 constant dollars. In cases where actual expenditures occurred over a period of years, escalation was based on the expenditure midpoint of the R&D phase or production lot.

5. Detailed System Data

Recurring production cost and prototype manufacturing cost will be used as data points. Following are summaries for each of the programs. Along with the summaries are explanations of how cost adjustments were made to ensure comparable data points.

M-1 Abrams Tank

The M-1 Abrams is a four man, highly mobile, fully tracked vehicle, with improved survivability provided by ballistic protection and compartmentalization. It is the United States' current main battle tank. Its mission is to destroy an enemy by using firepower from its 105mm main gun (and later a 120mm gun in the M1A1) and three secondary systems and by using its mobility and speed. Research and development was begun in 1973. The first units were fielded in 1979. The data for this program came from *U.S. Weapon Systems Costs, 1990* (Nicholas).

Production costs reflect the recurring portion of primary vehicle costs at Level 2 of the work breakdown structure. Development costs are the program's prototype manufacturing cost. It is necessary to isolate prototype manufacturing cost in order to gain an accurate cost of the hardware that went into the development models.

A ratio of development engineering cost to prototype manufacturing cost was used as a factor for adjusting the available development cost data. This was necessary to convert the available data, which included much more than just prototype manufacturing cost, to a smaller number reflecting only prototype manufacturing cost. Development cost for the

M-1 was then comparable to the six other programs' development costs. The factor used here was derived from the Baseline Cost Estimate (BCE) for the M-1 as follows:

Dev. Eng./Proto Manuf. = 1.37
Dev. Eng. = 1.37 * Proto Manuf.
Dev. Eng. + Proto Manuf = Proto Manuf + (1.37 * Proto Manuf)
233.92 = 2.37 * Proto Manuf
Proto Manuf = 233.92/2.37 = 98.7 .

M-60 Combat Tank

The M-60 Combat Tank is a diesel powered, fully tracked, armored vehicle with a 105mm main gun and four man crew. The M-60 has been improved since its original purchase in 1959, resulting in four model upgrades. Initial production for the M-60 was from 1959 to 1963, when it was upgraded and designated the M-60A1. The M-60 series was produced between 1959 and 1983 as the United States' main battle tank.

Cost data for this program was obtained from "An Evaluation of Competitive Procurement Methodologies Applicable to the Advanced Assault Amphibian Vehicle" (Corcoran, 1988). Research and development costs were not available at a level of detail that would permit identification of prototype manufacturing cost. In order to determine prototype hardware costs that would be consistent with the other programs, it was necessary to determine what portion of the total R&D cost could be allocated to prototype manufacturing cost. To do this, the development cost estimate used for the LVT(X) in the Center for Naval Analyses independent cost estimate was used as a proxy for determining prototype manufacturing cost for the M-60 (Kusek, 1984). In the LVT(X) estimate, prototype manufacturing is given as 19% of the total development cost. This was applied to the total R&D costs from the data to come up with the development cost.

The development cost was compared to results using the same development cost data and the methodology discussed in the M-1 case. This was done to check the

validity of using 19% of total development cost as an estimator of prototype manufacturing cost. Applying the same method used for the M-1, total R&D would have been divided by 2.37, plus a factor to account for government support. A factor for government support is necessary because government costs appear to have been included in the total development figure. The results of the two methods were compared. There was less than a three percent difference between the two methods. Hence, the figure using the 19% factor was deemed reasonable.

M-113 Armored Personnel Carrier

The M-113 is a fully tracked, light armored vehicle which serves as the basic squad (10 troops) carrier for the infantry. It is the base vehicle chassis for a family of vehicles which includes command post variants, cargo carriers, and mortar variants. The M-113 was produced from 1959 until 1982, undergoing several upgrades. Cost data for this program was obtained from an untitled study of the M-113 family of vehicles.

Research and development data did not include contracts which either modified or involved feasibility studies on the basic vehicle. The development costs are for prototypes that were built in the given years. Only original prototype vehicles are included in this data. Other prototypes were used, but were either the result of modifications to existing vehicles or test beds for subsystems. Inclusion of these vehicles would have reduced the average development cost of these vehicles relative to the other vehicles. The vehicle was upgraded to the M-113A1 in 1969. No upgraded vehicles are included in the data.

M-2/3 Bradley Fighting Vehicle

The M-2/3 is a fully tracked, lightly armored infantry and cavalry vehicle. It provides cross-country mobility and firepower to support mechanized infantry operations. The M-2/3 program started in 1979. Production is scheduled to end in 1993. Cost data for this

program was obtained from Cost Performance Reports (CPRs) from FY80 to FY89.

The available M-2/3 development data needed to be converted to costs that reflected only prototype manufacturing cost. The ratio of development engineering to prototype manufacturing cost was used in the same way that it was described in the M-1 case. The ratio used was 2.25, which was derived from the Bradley BCE.

M-109 Self Propelled Howitzer

The M-109 system consists of a 105mm howitzer gun mounted on a fully tracked carriage, which is propelled by a diesel engine. It provides direct field support artillery fire for infantry divisions and brigades. This system was produced from 1962 to 1967.

Cost data for this program was taken from "Cost Analysis Technical Report, M108 Howitzer, Light Self-Propelled, 105mm, M109 Howitzer, Medium, Self-Propelled, 155mm," March 1969. The level of detail for development costs was the same as the M-60. The same methodology used in the M-60 case was used here to arrive at a prototype manufacturing cost.

M-110 Self Propelled Howitzer

The M-110 is an 8-inch howitzer mounted on a fully tracked carriage. It is employed as a general support artillery weapon. The M-110 shares the same power train and chassis as the M-107, which was produced during the same timeframe. It was introduced in 1962; production of the original M-110 was completed in the late 1960's. Cost data for this program was obtained from CPRs from 1963 and 1971.

Research and development costs were identified for the M110 vehicle family, which included two other variants. Since all three variants used the same power train and chassis, it was appropriate to include the entire research and development cost. This cost, like the M-60 and M-109, did not allocate prototype manufacturing cost separately. This was

handled in the same way as the other two programs.

For all the programs evaluated, only the initial models were considered. Upgrades of programs would have affected the unit costs and would not have provided an accurate analysis of how production costs are influenced by development costs. The data indicate a shift in unit cost of the M110 between 1965 and 1966. There was no mention of a model upgrade during this time in the literature. It can be inferred that there was a change in the program that caused a shift in unit cost. For this reason, units produced from 1966 to 1972 were not included in the regression analysis because the shift in unit price after 1965 apparently indicates that there was a vehicle upgrade.

LVTP-7 Landing Vehicle Tracked

The LVTP-7 is an armored assault amphibian vehicle, propelled by two water jets while waterborne and tracks on land. It was designed to transport troops or stores to the beach from amphibious shipping. The program was begun in 1964 and has gone through upgrades and one service life extension program. Cost data was obtained from "A Case Study of the LVTP-7 Amphibian Tractor Program" (Bahnmaier, 1974). Derivation of prototype manufacturing cost was done in the same way as the M-60, M109, and M110. This vehicle was upgraded after the initial four year production run.

DERIVATION OF TFU PRODUCTION COST FOR THE TWO MODELS

The theoretical first unit (TFU) cost is defined as the cost of producing the number one unit in a production sequence. Development units are produced prior to this production unit.

Two sets of cost improvement curves are fit to the above data for each of the seven systems. The first set assumes the disjoint model of learning holds for each system, while

the second set assumes the sequential model. All systems were used for both models due to the lack of firm information concerning which model applies to each system.

Of the programs being studied, only the M-113 and M-109 showed any evidence of separate acquisition phases. This is because prototypes were produced over several years for demonstrating different characteristics. Because no reasonable learning curve could be determined for the other programs, a flat (100%) learning curve was assumed for all the programs during development. This flat learning curve applies only to the disjoint model, where there is no carryover knowledge in producing development units to producing production units. This is a reasonable assumption, because the number of development units will not directly affect the TFU cost of development units. It is also possible that "learning" may not have occurred between acquisition phases. This would happen if different vehicles were produced during different acquisition phases, such as concept exploration, engineering development, or test prototype. The sequential model, however, allows for learning to be carried over from development to production.

1. Disjoint Model

Production learning curve slopes were determined for each system based on recurring production costs and quantities produced. The learning curves were used to calculate the TFU cost of production units, T_{1P}.

2. Sequential Model

In order to determine TFU in the sequential model, it is necessary to include development units with production units to fit a learning curve for each system. The T_{1P} value from the derived learning curve is displaced from the y-axis by the number of development units plus one. The intersection of the y-axis and projected production learning curve is shown as T_{1P} in Figure 2.

3. Comparison of Disjoint and Sequential Values

First unit production costs in the disjoint model should be smaller for each system when compared to first unit production costs for each system in the sequential model. This is because first unit production costs in the disjoint model do not reflect any of the higher cost units from the development phase. Therefore, first unit production costs reflect only the production costs. In the sequential model, development learning is captured by the inclusion of development units in production first unit cost. The data in Table 1 support this in all cases except the M-60. For the M-60, there were a limited number of data points available for inclusion in the analysis, and the data were not of the same quality as the other systems. These two factors may have contributed to this unusual observation.

Table 1: TFU COMPARISON

DISJOINT MODEL

SYSTEM	PRODUCTION		DEVELOPMENT	
	T_{1P}	SLOPE	T_{1D}	SLOPE
M-1	5.71	.89	8.97	1.00
M-60	10.72	.75	2.17	1.00
M-113	.50	.88	.25	1.00
M-2/3	1.93	.87	2.49	1.00
M-109	88.89	.65	75.8	1.00
M-110	1.83	.78	10.5	1.00
LVTP-7	.44	.98	2.66	1.00

SEQUENTIAL MODEL

SYSTEM	DEVELOPMENT AND PRODUCTION	
	T_{1P}	SLOPE
M-1	12.02	.84
M-60	2.52	.88
M-113	.79	.86
M-2/3	3.73	.81
M-109	100.92	.65
M-110	41.5	.54
LVTP-7	4.82	.75

CER MODEL DEVELOPMENT AND COMPARISON

1. CER Development

The objective of the CER is to relate production TFU cost, as the dependent variable, to independent variables that reflect development cost, quantity, and time span for the candidate programs. CERs are developed and evaluated for both the disjoint and sequential models. Again, all systems are used in both models since no evidence exists for classifying systems into one category or the other and since this is an exploratory study for this weapon system commodity category. The emphasis is on finding a good statistical relationship between production TFU, the dependent variable, and a set of independent, potentially-predictive variables which model different characteristics of the development phase.

Independent Variables

The independent variables chosen had to meet the following criteria: there must be a sound, logical hypothesis describing how the variable affects cost; the value of the variable must be identifiable early on in the program life cycle; and the value of the variable must be identifiable for all the systems in the data base. (Hess and Romanoff, 1987, p.8)

The following candidate independent variables have been identified (in parenthesis is the abbreviation used to identify them in running the model):

- Development cost (totdev)
- Development quantity (devqty)
- Average development cost (avgdev)
- Production rate (prodrt)
- Development time span (devts)
- Time between start of development and start of production (devprod)
- TFU of development (t1dev)

- Year development started (devyr)
- Year production started (prodyr)

CER Development Methodology

Both models will be evaluated for their robustness in estimating cost. The estimated TFU can then be applied by using the appropriate model and learning curve rate to estimate program cost.

In the disjoint case, TFU_D can be used directly to estimate cumulative cost or specific unit cost for the program in question. To do this, use the standard learning curve function:

$$Y=AX^{b}$$

where Y = unit cost of X units
A = TFU_D
X = number of units
b = slope coefficient.

In the sequential case, TFUs resulting from the CER need to be converted to a TFU value that can be used with the standard learning curve function as described above. To do this, use:

$$TFU_D=TFU_S(DevQty+1)^{b}$$

In the regressions, t1d is used to denote first unit cost of each system in the disjoint model, and t1s is used to denote first unit cost of each system in the sequential model. TFU_D and TFU_S, respectively, are the resulting first unit cost from the disjoint and sequential CERs.

Before a regression is run, it is necessary to ensure that none of the independent variables are highly correlated. An assumption of the multiple regression model is that no exact linear relationship exists among two or more of the independent variables.

The instances where independent variables are highly correlated will result in dubious estimated regression coefficients as well as selection of variables that produce illogical results. A correlation matrix of independent variables for the weapon systems was calculated. The following pairs of independent variables were found to be highly correlated: average development cost and total development cost, average development cost and TFU of development units, total development cost and TFU of development units, year development started and year production started. These relationships among different measures of development costs are understandable in that all three are measures of some aspect of the system's development cost. In the case of the actual years of starting development and production for each system, a more precise measure of this relationship turned out to be the time span between starting development and starting production.

Including two or more of the highly correlated measures of development cost will degrade the model's ability to support hypothesis testing. This is true for including both year development started and year production started. Using all the above information to narrow the choices of independent variables, a series of multiple regressions was performed. The regressions were used to determine the best relationship between one or more of the independent variables and the TFU dependent variables for both disjoint and sequential models. One set of regressions were calulated for each of the two models to allow comparison of the cost drivers for the models.

2. CER Results

A stepwise regression program was used to provide detailed output in order to evaluate the significance of the regression equations. The following general criteria were used in judging the output CERs: significant t-ratios for independent variable coefficients, an R^2 greater than 80 percent, and an equation F-value of four or more.

Beginning with the sequential model data, variables were added to the model one by one. Variables that did not provide a statistically significant level in explaining cost were eliminated from the model. For both models, the average development cost, total development cost and TFU of development units were evaluated with the other variables to determine which measure of development cost was the strongest cost predictor. Additionally, the years of starting development and production were substituted for each other in the model to determine if either, taken separately, would be significant.

A summary of the regression results for the disjoint model is shown in Table 2 and for the sequential model in Table 3. In addition to the coefficient values and their t-ratios, the standard error of the regressions (S) and R-squared values are shown for each of the regression models.

Disjoint Model

The CER for the disjoint model is:

$$TFU_D = -1.54 + 1.18\,t1dev$$

Inclusion of time between start of development and start of production (devprod) as an independent variable adds to the model's fit to the data as evidenced by the increase in R^2. However, in considering this method of calculating the disjoint TFU, a variable containing the time between development and production is probably not appropriate. Additionally, this variable has a larger-than-desired significance level, and it has a nonintuitive sign. It is therefore not included in the final CER. The final model explains TFU_D as a function of TFU of development units.

TABLE 2: STEPWISE REGRESSION OF TFU (DISJOINT MODEL)

STEP	1	2
CONSTANT	-1.544	4.301
t1dev	1.175	1.143
T-RATIO	12.64	15.22
devprod		-2.7
T-RATIO		-2.01
S	6.20	4.89
R-SQUARED	96.96	98.49

TABLE 3: STEPWISE REGRESSION OF TFU (SEQUENTIAL MODEL)

STEP	1	2	3	4
CONSTANT	4.081	-9.540	5.246	7.345
avgdev	1.343	1.423	1.324	1.313
T-RATIO	7.64	16.02	17.60	31.12
devprod		6.23	4.69	4.85
T-RATIO		4.07	3.73	6.88
devts			-3.3	-4.9
T-RATIO			-2.30	-4.94
prodrt				0.0057
T-RATIO				2.76
S	11.3	5.59	3.89	2.17
R-SQUARED	92.12	98.47	99.44	99.88

Sequential Model

The CER for the sequential model is:

$$TFU_S = -9.54 + 1.42\,avgdev + 6.23\,devprod$$

As with the disjoint model, the independent variables chosen were examined from an intuitive

standpoint for their ability to explain the original hypotheses. Development time span (devts) is defined as the time from the beginning of development to the end of development. This variable was not included because it seems redundant when the variable for time between start of development and start of production (devprod) is included. Additionally, the inclusion of development time span does not significantly increase the size of the explained variation. Production rate (prodrt) was also not included in the final equation because it does not significantly increase the explained variation, nor does it strengthen the intuitive explanation of the model. Overfitting of the data is a serious consideration here, also.

The final equation contains average development cost (avgdev) and time span between development and production to predict TFUs. The inclusion of a variable that explains time spent in development is compatible with this model. The sequential model allows for carryover of knowledge gained during development. This explains the existence of a variable that accounts for cost as a function of the time spent in development.

CONCLUSIONS

Although considerable effort was required to develop a consistent and comparable database for this approach, we recognize that the data utilized in this study are not ideal. Ideal data would consist of two sets of systems, one set produced under the disjoint model and the other set produced under the sequential model. This would permit a reasonable comparison of the development phase cost drivers of first unit production cost for the two different models.

The data we actually used for this analysis are not ideal for two reasons. First, we do not know *a priori* which model is appropriate for which system. This necessitated our approach of using all systems to test both models. Second, we do not have complete

expenditure profile data on all systems. This resulted in our having to estimate some profiles which, in turn, may have affected the cost improvement rates we obtained for the systems under the two different models. For example, the M-60 data appeared to not follow the general trends revealed by the other systems in our sample. However, the fits of our CERs to these data indicate that almost all of the variance in first unit production cost is explained by the independent variables for both of the two development-to-production models.

Hence, we are reasonably confident in the following conclusions. For the disjoint model, production TFU cost can be explained by development first unit cost. For the sequential model, production TFU cost is explained by average development cost and the time span between start of development and start of production.

If the acquisition strategy for a weapon system, or other empirical evidence, clearly delineates which model, either the disjoint or sequential model, is appropriate, then the results shown here can provide alternative, independent means for estimating production TFU costs. If one model is not preferred over the other, then both can be employed, with some averaging technique used, to provide an alternative estimate for production TFU cost.

Since this approach appears to be a viable technique for obtaining an estimate of production TFU cost which is independent of estimates based upon production characteristics, we recommend that similar analyses be undertaken for other major commodity types of weapon systems to see if similar results are obtained.

REFERENCES

"Advanced Assault Amphibious Vehicle, Average Unit Rollaway Cost Estimate," September 1987.

"Advanced Assault Amphibious Vehicle, Preliminary Life Cycle Cost Estimate," May 1988.

Acker, David D., *Defense Manufacturing Management Guide for Program Managers*, Defense Systems Management College, 1989.

Allard, Scott M., et al. "Electronics Development to Production Cost Relationships," Management Consulting and Research, Inc., April 1990.

Batchelder, C. A., et al., *An Introduction to Equipment Cost Estimating*, RAND Corp., RM-6103-SA, 1969.

Bahnmaier, William W., Marine Corps Systems Acquisition Management-A Case Study of the LVTP-7 Amphibian Tractor Program, M.S. Thesis, Naval Postgraduate School, Monterey, California, June 1974.

Corcoran, Michael A., An Evaluation of Competitive Procurement Methodologies Applicable to the Advanced Assault Amphibian Vehicle, M.S. Thesis, Naval Postgraduate School, Monterey, California, December 1988.

"Cost Analysis Technical Report, M108 Howitzer, Light Self- Propelled, 105mm, M109 Howitzer, Medium, Self-Propelled, 155mm", U.S. Army Weapons Command Cost Analysis Office, March 1969.

"Cost Performance Report DA-04-200-ORD-545", M-110 Vehicle Family, June 1963.

"Cost Performance Report DAAG05-70-C0894 ESP", M-110 Vehicle Family, December 1971.

"Cost Performance Reports", Bradley Fighting Vehicle, 1980-1989.

Fisher, Gene H., *Cost Considerations in Systems Analysis*, RAND Corp., R-490-ASD, 1970.

Fitzgerald, David M., Program Manager's Guide, Naval Postgraduate School, Monterey, California, 1990.

Fox, J. Ronald, *Arming America: How the U. S. Buys Weapons*, Harvard University Press, 1974.

Gaioni, Steven and Polley, Allan, Parametric Cost Estimation Applied to Marine Corps Medium-Lift Helicopters, M.S. Thesis, Naval Postgraduate School, Monterey, California, December 1990.

Gardner, Thurman D., et al., "The Relationship Between Tactical Missile's Development Unit Cost and Production Unit Cost," Science Applications International Corporation, September 1990.

Hess, R. W. and Romanoff, H. P., Aircraft Airframe Cost Estimating Relationships, RAND Corp.,R-3255-AF, December 1987.

Intriligator, Michael, *Econometric Models, Techniques, and Applications*, Prentice Hall, Inc., 1978.

Jane's Armour and Artillery, various editions, Jane's Information Group, various dates.

Kusek, Pete, "LVT(X) Independent Cost Estimate (ICE)," Center for Naval Analysis, CRM 84-13, August 1984.

Marine Corps Gazette, "AAAV Program Nears Milestone," September 1991.

Nicholas, Ted G., *U.S. Weapon Systems Costs, 1990*, Data Search Associates, 1990.

Ostwald, Phillip F., *Cost Estimating for Engineering and Management*, Prentice Hall, Inc., 1974.

Perry, Robert, et al., System Acquisition Strategies, RAND Corp., R-733-PR/ARPA, 1971.

Pindyck, R. S. and Rubinfeld, D. C., *Econometric Models and Economic Forecasts*, McGraw-Hill Book Company, 1976.

Sovereign, Michael G., "Survey of Project Cost Estimation," Unpublished Manuscript, ND.

Stewart, Rodney D. and Wyskida, Richard M., *Cost Estimator's Reference Manual*, John Wiley & Sons, 1987.

Systems Planning Corporation, "Tracked Vehicle Resource Analysis and Display (TREAD) Cost Model," November 1978.

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